OPERATION OF NRL HOMOPOLAR GENERATOR INTO PARALLEL ENERGY STORAGE INDUCTOR

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Summary

A 170-μH solenoid has been constructed and used as an energy storage inductor with the existing NRL self-excited HPG. This use of a separate energy storage coil results in minimal interaction with the excitation coil and permits operation at higher voltages. The energy storage inductor has been designed to operate under water at a megavolt. The circuit and energizing of the two parallel inductors is described. The inductive storage has been used in conjunction with opening switches to generate output pulses with 30-μs risetime and an e-fold decay time determined by the load resistance.

Introduction

A pulsed power system[1] in use at the Naval Research Laboratory employes inductive and inertial energy storage. In this system a self-excited homopolar generator (HPG) serves to transfer rotational energy from flywheels to magnetic energy in the storage inductor. A single 1.4-mH solenoid inductor enclosing the flywheels can be energized to 60 kA and serves both as energy storage and as excitation field coil for the HPG. When this inductor is discharged into a load resistance (by means of opening switches) the output pulse voltage is limited to 200 kV by the insulation of the inductor.

At the previous conference[2] we proposed using separate inductors for energy storage and HPG excitation field. Parallel connection of the low-impedance HPG would provide isolation of the storage and excitation inductors and permit the storage inductor to be operated at much higher voltages. The theoretical analysis presented for this circuit concept showed that the inertial-to-inductive energy transfer efficiency was relatively constant over a wide range of inductance from 0.1 mH to 1.0 mH. Specifically, if the energy storage circuit time constant were 1 s, an energy of 2 MJ could be obtained with an initial flywheel speed of 260 rps. As a consequence an increase in current as well as voltage for the pulse output appeared well within the realm of possibility.

In this paper we will describe the implementation of this concept through design and construction of a separate low inductance (170 μH) energy storage coil and its operation as an addition to the existing HPG and excitation coil.

Energy Storage Inductor

The energy storage inductor is made of 51-mm wide by 152-mm thick copper conductor fabricated into the form of a single layer solenoid having a mean diameter of 1.04 m. Each turn is separated by a 25-mm thickness of polyurethane insulation. Although a high inductor current may be achieved by lower inductance of the storage coil, the mechanical-to-magnetic energy transfer efficiency is critically dependent on maintaining a large L/R time-constant for the storage coil circuit.

During the detailed design and manufacture of the coil, a long L/R time constant appeared to be an elusive goal for a number of reasons. First, manufacture was greatly facilitated by fabricating the coil with 7/8 turn segments. The resulting number of joints contribute a not insignificant contact resistance. Even more significantly, the copper alloy used was found to have a resistivity of 2.3 μΩ-cm (compared to 1.7μΩ-cm for ETP copper). Finally, the detailed design revealed that the connecting bus bar resistance would be much greater than originally anticipated. The final coil design uses 21 of the 7/8 turn segments for an 18-3/8 turn solenoid with a calculated inductance of 170 μH. The resistance of the energy storage circuit (measured with a four-terminal bridge) is 320μΩ. Of this the coil itself contributes 180 μΩ and the switches and their connections contribute 40 μΩ. The remaining 100 μΩ is due to the interconnecting bus bars and their contact resistances. The resulting 0.5-s time-constant is a compromise between the contradictory goals of low-inductance (for high current) and long time-constant (for high energy transfer efficiency).

Figure 1 is a photograph of the completed energy storage coil mounted in the (empty) water tank and connected to switches and load resistor at the left. It is planned to ultimately operate the coil under water where the 25 mm gaps between turns should permit operation at 1 MV.

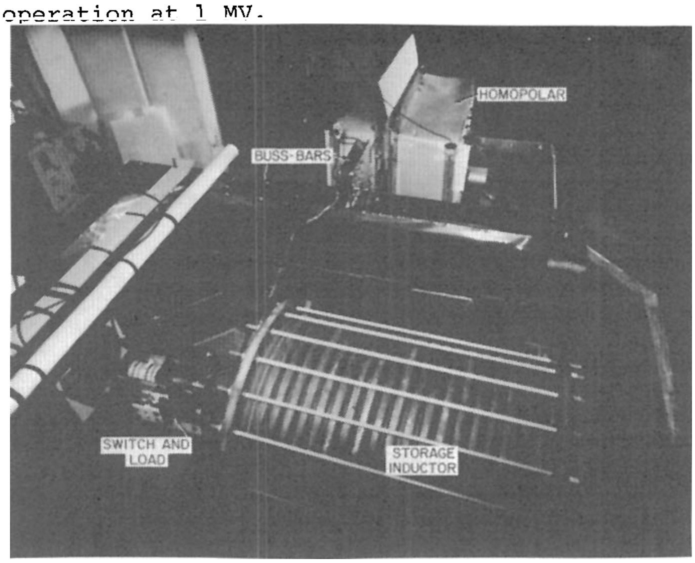

Fig. 1. Inductive Energy Pulse Generator.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1983	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Operation Of NRL Homopolar Generator Into Parallel Energy Storage Inductor	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory Washington, D.C. 20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Energizing Storage Inductor

Fig. 2 is a schematic diagram of the electrical circuit for the two coils and HPG. The original 1.4-mH coil surrounding the HPG flywheels now serves only to provide the exciting field. Four of the rim brushes on each wheel are connected to this exciter coil, but insulated from the other rim brushes, so starter current is confined to the exciter coil. The rim brushes serve as making switches to start current flow from flywheels to coils. The low voltage (10-kV) circuit breaker and 0.4-Ω resistor in the exciter circuit are needed simply to open that circuit and dissipate the current prior to lifting the brushes after each shot. The other thirty rim brushes on each flywheel are connected to separate collectors which are in turn attached to the busbars leading to the energy storage coil.

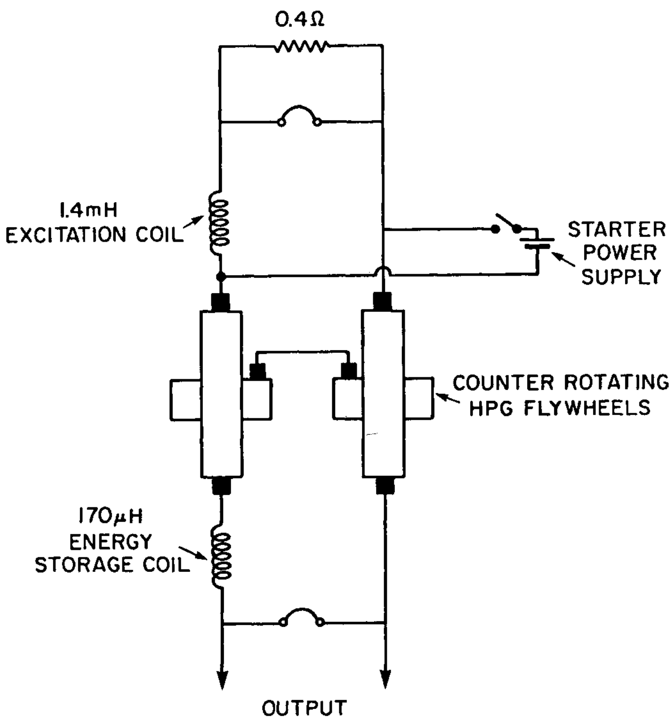

Fig. 2. Schematic Electrical Circuit.

In addition to the new rim brush collector plates for each flywheel assembly, other modification to the HPG and exciter coil included separation of the exciter coil into two coils which can be parted to connect the energy storage coil busbars to the HPG and extension of the center conductor to connect the two axle brush sets.

Fig. 3 is a photograph of oscilloscope traces of the time-dependent currents in the energy storage circuit (top trace) and exciter circuit (lower trace) resulting from a shot with initial flywheel speed of 210 rps. These traces start at the instant when the starter current is turned on. In the lower trace, the exciter current is seen to rise to the 950 A provided by the starter. The brushes are pushed in to connect the HPG to the two coils one second later and both currents increase as the HPG voltage increases due to self-excitation. Maximum currents of 70 kA in storage coil and 10 kA in exciter coil are achieved three seconds after the brushes make contact. Both currents drop to zero (abruptly when viewed on this time scale) when the circuit breakers are opened. For this shot, the circuit breakers were purposely opened after the current maxima in order to obtain a measurement of the peak current values.

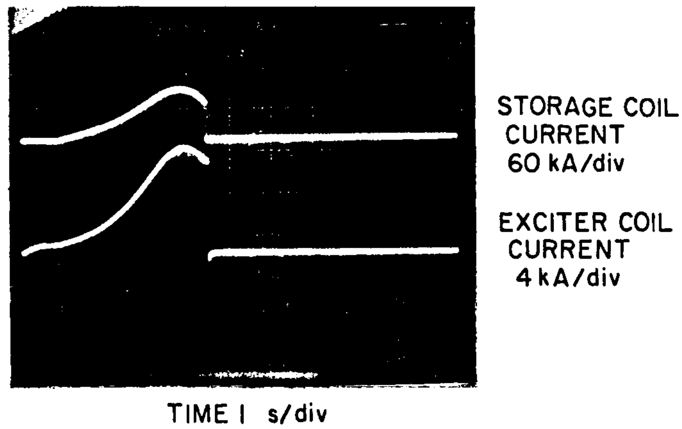

Fig. 3. Time-Dependent Inductor Currents Observed from a Shot with Wheel Speed of 210 Hz.

The current in the energy storage inductor has been calculated by a simultaneous numerical integration of the voltage equations for the two circuits and the torque equation for the flywheels. The resulting peak storage coil current as a function of the value of initial flywheel speed is shown as the solid line in Fig. 4. Some measured values are shown as the open circles on the same graph.

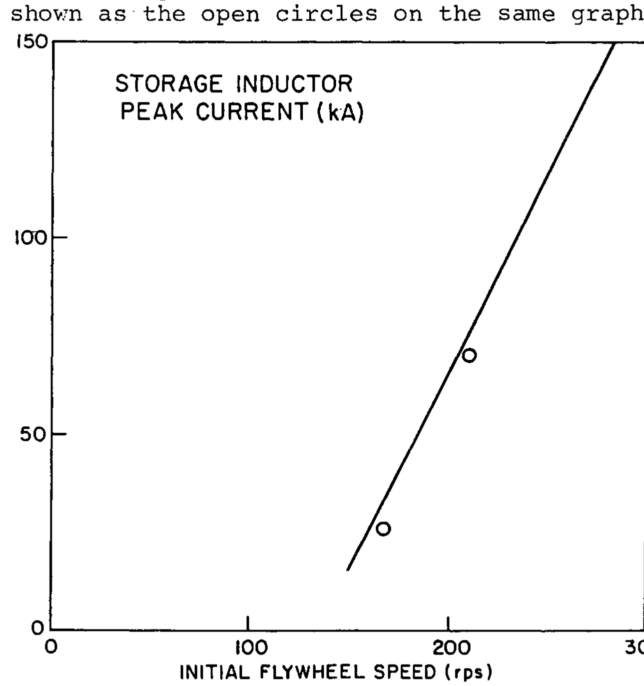

Fig. 4. Calculated Values of Speed-Dependent Peak Current. The Two Circled Points are Measured Values.

Current Collectors

All metal fiber brushes are used for current collection at the flywheel rims because of the high speed of the slipring there. The current limit established for these brushes in the original configuration was due to magnetic force failure. The magnetic force responsible is proportional to the product of excitation field strength and current per brush. Although current per brush is greater in the present mode of operation, the exciter current (and B field) is less, and this failure is not expected to occur unless currents exceed 5 kA per brush. However, at currents greater than 2.5 kA per brush, current densities will be higher than previously experienced and resultant joule heating is greater and may result in undesirably high temperatures at the contact surface.

The solid copper-graphite brushes used on the axle sliprings have in the past[2] operated at a current density of 9 MA/m^2 at current of 60 kA. If machine current is doubled the current density will be greater than values customarily used in the design of pulsed machines.

In view of these concerns the HPG has been instrumented to measure brush voltage drops. On each flywheel system, one rim brush is electrically insulated from the rest and used to provide a reference potential for the flywheel rim. The measured brush voltage is the voltage difference between the reference brush and the brush collector plate (output terminal). These brush voltages (typically one volt) must be measured at a wheel rim potential which is about 100 V above ground potential. Consequently, the measurement devices are isolated from ground by fiber optic links. In each of these, optical fibers carry an analog light signal from a batter powered link transmitter to a receiver at ground potential. One axle brush on each flywheel has also been insulated to provide an axle slipring reference potential and permit similar measurement of axle brush voltage drops.

Figure 5 illustrates some results obtained from these measurements. This figure shows the measured voltage drop plotted as a function of the current per brush for a brush testing shot in which only the exciter was energized through four brushes on each wheel and current was allowed to continue well beyond its peak before being interupted. For this shot slipring speed was 300 m/s and initial normal contact force was 13 N per brush. The measured voltage is the voltage drop across the contact surface plus the drop developed across the resistance of the flexible current shunts connecting the brush to the collector. In this figure, the voltage difference between the decreasing portion of the pulse and the rising portion is due to the resistance increase resulting from overheating of these current shunts.

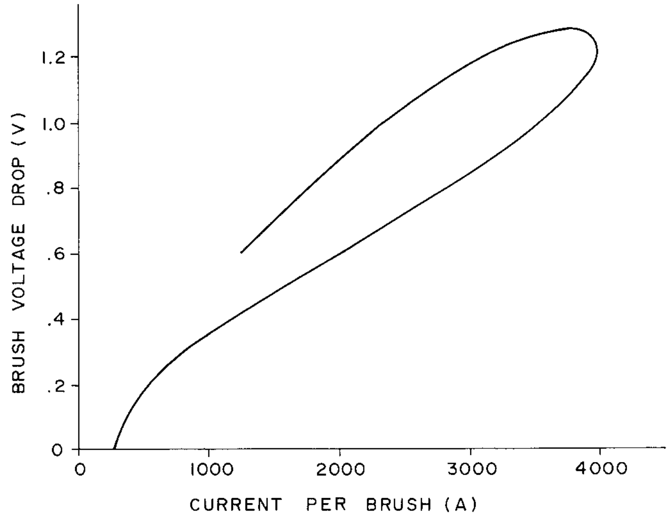

Fig. 5. Results of Brush Testing Shot.

Pulse Generation

The new 170-μH storage inductor has been used as a source for delivering current pulses into a 0.25-μ load resistance. The current pulses were generated with staged switching using explosively actuated circuit breakers (EACB's) to carry the current while the inductor is energized and using a wire fuse to shorten the pulse risetime.

Parallel EACB's must be used at higher currents. For the time required to energize the inductor from the HPG, the 1.73-mm wall conductor used in the "tube switch" EACB[3] can be operated at 50 kA. Three of these tube switches may be needed if currents exceed 100 kA. A slightly different approach is being tried to reduce the number of switches. In this approach a single thick-copper conductor (6.35-mm thick x 10-cm wide) explosively operated flat switch[4] carries the initial current. Since this is a slow opening switch, it is paralleled by a single tube switch EACB which opens 10 ms later. The switch holdoff has been demonstrated at 100 kV/explosive gap (8-10 kV/cm voltage holdoff) when operated in air. Preliminary tests show that the switch opens well under water. It is hoped that similarly high withstand voltage will be possible when in this insulating medium.

A schematic diagram of the equivalent circuit for this pulse generator is shown in Fig. 6. The two EACB's are fired with triggering circuits which use diode isolation to prevent induced magnetic fields from causing prefiring of the detonators. The switches can be seen in the left of the photograph of Fig. 1. The slow, flat switch (C.B.-1) is the one nearest the front and the 12-stage tube switch (C.B.-2) is in the center. Just behind the tube switch is a fuse holder containing a 1.78-m long, No. 15 gauge copper wire fuse.

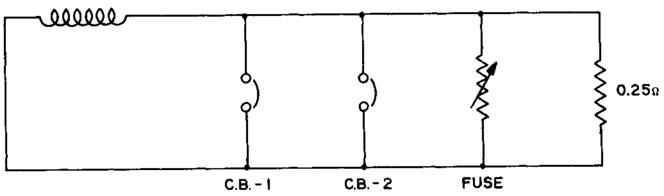

Fig. 6. Switching Circuit Used to Discharge 170 -μH Storage Coil into 0.25 Ω Load Resistor.

The performance of the pulse generator is illustrated by the oscilloscope traces of Fig. 7. The oscilloscope traces start when the tube EACB (C.B.-2) is triggered. The arc voltage of this EACB commutates its current into the fuse. (The EACB current falls from 50 kA to zero as the fuse current rises to a 50 kA peak at 120 μs.) During the interval from 120 μs to 200 μs the fuse current falls to zero as its resistance increases and the current is transferred into the load resistor. The 3 kV seen across the load resistor during the inerval of 90 μs to 140 μs is due to the arc voltage of the EACB. Opening of the fuse drives the current into the load resistor with a 30 μs risetime.

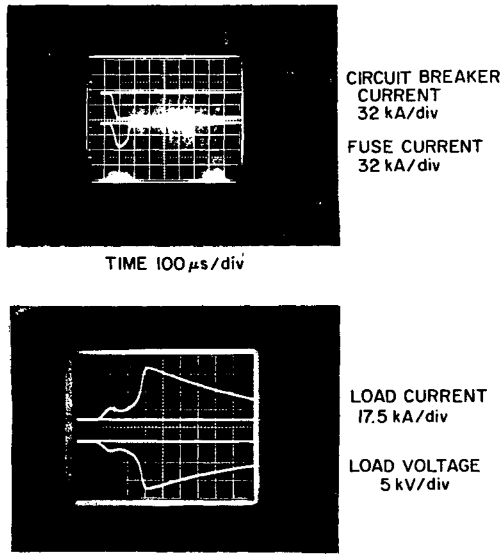

Fig. 7. Top-Circuit Breaker (C.B. -2) and Fuse Currents During Typical Shot Bottom-Current and Voltage on 0.25 Ω Load Resistor.

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